OUTER PLANET ICY SATELLITES

by

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GLOSSARY

Bond Albedo: The fraction of the total incident radiation reflected by a planet or satellite.

Carbonaceous (C-Type) Material: Carbon-silicate primordial material rich in simple organic compounds. C-type material is spectrally flat, and it exists on the surfaces of several outer planet satellites.

Differentiation: Melting and chemical fractionation of a planet or satellite into a core and mantle.

D-Type Material: Primordial, low albedo material believed to be rich in organic compounds. It is redder than C-type material.

Geometric Albedo: The ratio of the brightness at a phase angle of zero degrees (full illumination) compared with a diffuse, perfectly reflecting disk of the same size.

Greenhouse Effect: The heating of the lower atmosphere of a planet or satellite by the absorption of visible radiation and subsequent reradiation in the infrared.

Lagrange Points: Equilibrium points in the orbit of a planet or satellite around its primary.

Magnetosphere: The region around a planet dominated by its magnetic field and associated charged particles.

Apposition Effect: The surge in brightness as a satellite becomes fully illuminated to the observer.

Phase Angle: The angle between the observer, the satellite, and the sun.

Phase Integral: The integrated value of the function which describes the directional scattering properties of a surface.

Primary Body: The celestial body (usually a planet) around which a satellite, or secondary, orbits.

Regolith: The surface layer of rocky debris created by meteorite impacts.

Roche's Limit: The distance (equal to 2.44 times the radius of the primary) at which the tidal forces exerted by the primary on the satellite equal the internal gravitational forces of the satellite.

Synchronous Rotation: A dynamical state caused by tidal interactions in which the satellite presents the same face towards the primary.

An outer planet icy satellite is any one of the celestial bodies in orbit around Jupiter, Saturn, Uranus, Neptune, or Pluto. They range from large, planet-like geologically active worlds with significant atmospheres, such as Triton, to tiny irregular objects tens of kilometers in diameter. These bodies are all believed to have as major components some type of frozen volatile, primarily water ice, but also methane, ammonia, nitrogen, carbon monoxide, carbon dioxide, or sulfur dioxide existing alone or in combination with other volatiles. The outer five planets have among them a total of 58 known satellites. There undoubtedly exist many more undiscovered small satellites in the outer solar system. Th relative sizes of the satellites of these four planets is illustrated in Figure 1. Table I is a summary of their characteristics. This chapter covers the satellites of Jupiter, Saturn, Uranus, and Neptune, except Io, Triton, and Titan (see IO, TITAN, TRITON, and PLUTO-CHARON).

I. Summary of Characteristics

A. Discovery

None of the satellites of the outer planets were known before the invention of the telescope. When Galileo turned his telescope to Jupiter in 1610, he discovered the four large satellites in the Jovian system. His observations of their orbital motion around Jupiter in a manner analogous to the motion of the planets around the sun provided important evidence for the acceptance of the heliocentric (sun-centered) model of the solar system. These four moons - Io, Europa, Ganymede, and Callisto - are sometimes called the Galilean satellites.

In 1655 Christian Huygens discovered Titan, the giant satellite of' Saturn. Later in the seventeenth century, Giovanni Cassini discovered the four next largest satellites of Saturn. It was not until over one hundred years later that the next satellite discoveries were made: the Uranian satellites Titania and Oberon and two smaller moons of Saturn. As telescopes acquired more resolving power in the nineteenth century, the family of satellites grew (see Table I). The smallest satellites of Jupiter and Saturn, and all the small satellites of Uranus and Neptune (except Nereid), were discovered during flybys of the Pioneer and Voyager spacecraft (see Table II).

The natural planetary satellites are generally named after figures in classical Greek and Roman mythology who were associated with the namesakes of their primaries. THey are also designated by the first letter of their primary and an Arabic numeral assigned in order of discovery: Io is J1, Europa J2, etc. When satellites are first discovered but not yet confirmed or officially named, they are known by the year in which they were discovered, the initial of the primary, and a number assigned consecutively for all solar system discoveries, e.g., 1980J27. Official names for all satellites are assigned by the International Astronomical Union.

After planetary scientists were able to map geologic formations of the satellites from spacecraft images, they named many of the features after characters or locations from Western and Eastern mythologies.

B. Physical and Dynamical Properties

The motion of a satellite around the center of mass of itself and its primary defines an ellipse with the primary at one of the foci. The orbit is defined by three primary orbital elements (1) the semimajor axis, (2) the eccentricity, and (3) the angle made by the intersection of the plane ot the orbit and the plane of th primary's spin equator (the angle Of inclination) . The orbits are said to be regular if they are in the same sense of direction (the prograde sense) as that determined by the rotation of the primary, and if their eccentricities and inclinations are low. The orbit of a satellite is irregular if its motion is in the opposite (or retrograde) sense of motion, if it is eccentric, or if it has a high angle of inclination. The majority of the outer planets' satellites move in regular, prograde orbits. Many of the satellites that move in irregular orbits are believed to be captured objects.

Most of the planetary satellites present the same hemisphere toward their primaries, a situation which is the result of tidal evolution. When two celestial bodies orbit each other, the gravitational force exerted on the near side is greater than that exerted on the far side. The result is an elongation of each body to form tidal bulges, which can consist of either solid, liquid, or gaseous (atmospheric) material. The primary will tug on the satellite's tidal bulge to lock its longest axis onto the primary-satellite line. The satellite, which is said to be in a state of synchronous rotation, keeps the same face toward the primary. Since this despun state occurs rapidly (usually within a few million years), most natural satellites are in synchronous rotation.

The satellites of the outer solar system are unique worlds, each representing a vast panorama of physical processes. The small satellites of Jupiter and Saturn are irregular chunks of ice and rock, perhaps captured asteroids, which have been subjected to intensive meteoritic bombardment. Several of the satellites, including the Saturnian satellite Phoebe and areas of the Uranian satellites, are covered with C-type material, the dark, unprocessed, carbon-rich material found on the C class of asteroids (see ASTEROIDS). The surfaces of other satellites such as Hyperion and the dark side of Iapetus contain D-type primordial matter (named afer the D class of asteroids), which is spectrally red and believed to be rich in organic compounds. Both D- and C-type material are common in the outer solar system. Because these materials represent the material from which the solar system formed, understanding their occurrence and origin will yield clues on the state and early evolution of the solar system. Iapetus presents a particular enigma: one hemisphere is ten times more reflective than the other.

Before the advent of spacecraft exploration, planetary scientists expected the icy satellites to be geologically dead worlds. They assumed that heat sources were not sufficient to have melted their mantles to provide a source of liquid or semi-liquid ice or ice-silicate slurries. Reconnaissance of the icy satellite systems of the four outer giant planets by the two Voyager spacecraft uncovered a wide range of geologic processes, including currently active vulcanism on Io and Triton. At least two additional satellites (Europa and Enceladus) may have current activity. The medium-sized satellites of Saturn and Uranus are large enough to have undergone internal melting with subsequent differentiation and resurfacing. Among the Galilean satellites, only Callisto lacks evidence for periods of activity after formation.

Recent work on the importance of tidal interactions and subsequent heating has provided the theoretical foundation to explain the existence of widespread activity in the outer solar system. Another factor is the presence of non-ice components, such as ammonia hydrate or methanol, which lower the melting point of near-surface materials. Partial melts of water ice and various contaminants - each with their own melting point and viscosity - provide material for a wide range of geologic:

activity. The realization that such partial melts are important to understanding the geological history of the satellites has spawned an interest in the rheology (viscous properties and resulting flow behavior) of various ice mixtures and exotic phases of ices that exist at extreme temperatures or pressures. Conversely, the types of features observed on the surfaces provide clues to the likely composition of the satellites' interiors.

Because the surfaces of so many outer planet satellites exhibit evidence of geologic activity, planetary scientists have begun to think in terms of unified geologic processes that function throughout the solar system. For example, partial melts of water ice with various contaminants could provide flows of liquid or partially molten slurries which in many ways mimic terrestrial or lunar lava flows formed by the partial melting of mixtures of silicate rocks. The ridged and grooved terrains on satellites such as Ganymede, Enceladus, Tethys, and Miranda may all have resulted from similar tectonic activities. Finally, explosive volcanic eruptions occurring on Io, Triton, Earth, and possibly Enceladus, may all result from the escape of volatiles released as the pressure in upward-moving liquids decreases. (see PLANETARY VULCANISM)

II. Formation of Satellites

A. Theoretical Models

Because the planets and their associated moons condensed from the same cloud of gas and dust at about the same time, the formation of the natural planetary satellites must be addressed within the context of the formation of the planets. The solar system formed 4.6 $\pm$ 0.1 billion years ago. This age is derived primarily from radiometric dating of meteorites, which are believed to consist of primordial, unaltered matter. In the radiometric dating technique, the fraction of a radioactive isotope (usually rubidium, argon, or uranium), which has decayed into its daughter isotope, is measured. Since the rate at which these isotopes decay has been measured in the laboratory, it is possible to infer the time elapsed since formation of the meteorites, and thus of the solar system. (See ORIGIN OF THE SOLAR SYSTEM)

The sun and planets formed from a disk-shaped rotating cloud of gas and dust known as the proto-solar nebula. When the temperature in the nebula cooled sufficiently, small grains began to condense. The difference in solidification temperatures of the constituents of the proto-solar nebula accounts for the major compositional differences of the satellites. Since there was a temperature gradient as a function of distance from the center of the nebula, only those materials with high melting temperatures

(e. g., silicates, iron, aluminum, titanium, and calcium) solidified in the central (hotter) portion of the nebula. The Earthts Moon consists primarily of these materials. Beyond the orbit of Mars, carbon, in combination with silicates and organic molecules, condensed to form the carbonaceous material found on C-type asteroids. Similar carbonaceous material is found on the surfaces of the Martian moon Phobos, several of the Jovian and Saturnian satellites, regions of the Uranian satellites, and posssibly Triton and Charon. Beyond the outer region of the asteroid belt, formation temperatures were sufficiently cold to allow water ice to condense and remain stable. Thus , the Jovian satellites are primarily ice-silicate admixtures (except for Io, which has apparently outgassed all its water). On Saturn and Uranus, these materials are joined by methane and ammonia, and their hydrated forms. For the satellites of Neptune and Pluto, formation temperatures were low enough for other volatiles, such as nitrogen, carbon monoxide, and carbon dioxide to exist in solid form. In general, the satellites which formed in the inner regions of the solar system are denser than the outer planets' satellites, because they retained a lower fraction of volatile materials.

After small grains of material condensed from the proto-solar nebula, electrostatic forces caused them to stick together. Collisions between these larger aggregates caused meter-sized particles, or planetesimals, to be accreted. Finally, gravitational collapse occurred to form larger, kilometer-sized planetesimals. The largest of these bodies swept up much of the remaining material to create the protoplanets and their companion satellite systems. One important concept of planetary satellite formation is that a satellite cannot accrete within Roche's limit, the distance at which the tidal forces of the primary become greater than the internal cohesive forces of the satellite.

The formation of the regular satellite systems of Jupiter, Saturn, and Uranus is sometimes thought to be a smaller scaled version of the formation of the solar system. A density gradient as a function of distance from the primary does exist for the regular system of small, inner Neptunian satellites and for the Galilean satellites (see Table I). This implies that more volatiles (primarily ice) are included in the bulk composition as the distance increases. However, this simple scenario cannot be applied to Saturn or Uranus because their regular satellites do not follow this pattern.

The retrograde satellites are probably captured asteroids or large planetesimals left over from the major episode of planet formation. Except for Titan and Triton, the satellites are too small to possess gravitational fields sufficiently strong to retain an appreciable atmosphere against thermal escape.

B. Evolution

Soon after the satellites accreted, they began to heat up from the release of gravitational potential energy. An additional heat source was provided by the release of mechanical energy during the heavy bombardment of their surfaces by remaining debris. The satellites Phobos, Mimas, and Tethys all have impact craters caused by bodies that were nearly large enough to break them apart; probably such catastrophes did occur. The decay of radioactive elements found in silicate materials provided another major source of heat. The heat produced in the larger satellites was sufficient to cause melting and chemical fractionation; the dense material, such as silicates and iron, went to the center of the satellite to form a core, while ice and other volatiles remained in the crust. A fourth source of heat is provided by tidal interactions. When a satellite is being tidally despun, the resulting frictional energy is dissipated as heat. Because this process happens very quickly for most satellites (-10 million years), another mechanism involving orbital resonances among satellites is believed to cause the heat production required for more recent resurfacing events. Gravitational interactions tend to make the orbital periods of the satellites within a system multiples of each other. In the Galilean system, for example, Io and Europa complete four and two orbits, respectively, for each orbit completed by Ganymede. The result is that the satellites meet each other at the same point in their orbits. The resulting flexing of the tidal bulge induced on the bodies by their mutual gravitational attraction causes significant heat production in some cases. (see IMPACT PROCESSES AND GIANT IMPACTS, and SOLAR SYSTEM DYNAMICS)

Some satellites, such as the Earthts Moon, Ganymede, and several of the Saturnian satellites underwent periods of melting and active geology within a billion years of their formation and then became quiescent. Others, such as Io and Triton, and possibly Enceladus and Europa, are currently geologically active. For nearly a billion years after their formation, the satellites all underwent intense bombardment and cratering. The bombardment tapered off to a slower rate and presently continues. By counting the number of craters on a satellite's surface and making certain assumptions about the flux of impacting material, geologists are able to estimate when a specific portion of a satellite[s] surface was formed. Continual bombardment of satellites causes the pulverization of both rocky and icy surfaces to form a covering of fine material known as a regolith.

Many scientists expected that most of the craters formed on the outer planets' satellites would have disappeared due to viscous relaxation. The two Voyager spacecraft revealed surfaces covered with craters which in many cases had morphological similarities to those found in the inner solar system, including central pits, large ejects blankets, and well-formed outer walls. Scientists now believe that silicate mineral contaminants or other impurities in the ice provide the extra strength required to sustain impact structures.

Planetary scientists classify the erosional processes effecting satellites into two major categories: endogenic, which includes all internally produced geologic activity; and exogenic, which encompasses the changes brought by outside agents. The latter category includes the following processes: 1) meteoritic bombardment and resulting gardening and impact. volatization; 2) magnetospheric interactions, including sputtering and implantation of energetic particles; 3) alteration by high energy ultraviolet photons; and 4) accretion of particles from sources such as planetary rings.

Meteoritic bombardment of icy bodies acts in two major ways to alter the optical characteristics of the surface. First, the impacts excavate and expose fresh material (cf., the bright ray craters on Ganymede). Second, impact volatization and subsequent escape of volatiles results in a lag deposit enriched in opaque, dark materials. The relative importance of the two processes depends on the flux, size distribution, and composition of the impacting particles, and on the composition, surface temperature, and mass of the satellite. For the Galilean satellites, older geologic regions tend to be darker and redder. Both the Galilean and Saturnian satellites tend to be brighter on the hemispheres which lead in the direction of orbital motion (the so-called "leading" side, as opposed to the "trailing" side) ; this effect is thought to be due to preferential micrometeoritic gardening on the leading side. The Uranian satellites show no similar dichotomy in albedo, but their leading sides do tend to be redder, possibly due to the accretion of reddish meteoritic material on that hemisphere.

For satellites that are embedded in planetary magnetospheres, their surfaces are affected by magnetospheric interactions in three ways: 1) chemical alterations; 2) selective erosion, or sputtering; and 3) deposition of magnetospheric ions. In general, volatile components are more susceptible to sputter erosion than refractory ones. The overall effect of magnetospheric erosion is thus to enrich surfaces in darker, redder opaque materials. A similar effect is believed to be caused by the bombardment of UV photons, although much fundamental laboratory work remains to be done in order to determine the quantitative effects of this process.

III. OBSERVATIONS OF SATELLITES

A. Telescopic Observations

1. Spectroscopy

Before the development of interplanetary spacecraft, all observations from Earth of objects in the solar system were obtained by telescopes. One particularly useful tool of planetary astronomy is spectroscopy, or the acquisition of spectra from a celestial body.

Each component of the surface or atmosphere of a satellite has a characteristic pattern of absorption and emission bands. Comparison of the astronomical spectrum with laboratory spectra of materials which are possible components of the surface yields information on the composition of the satellite. For example, water ice has a series of absorption features between 1 and 4 microns. The detection of these bands on three of the Galilean satellites and several satellites of Saturn and Uranus demonstrated that water ice is a major constituent of their surfaces. Other examples are the detections of SO_2 frost on the surface of Io, methane in the atmosphere of Titan, nitrogen and carbon dioxide on Triton, and carbon monoxide on Pluto.

2. Photometry

Photometry of planetary satellites is the accurate measurement of radiation reflected to an observer from their surfaces or atmospheres. These measurements can be compared to light scattering models that are dependent on physical parameters, such as the porosity of the optically active upper surface layer, the albedo of the material, and the degree of topographic roughness. These models predict brightness variations as a function of solar phase angle (the angle between the observer, the sun, and the satellite). Like the Earth's Moon, the planetary satellites present changing phases to an observer on Earth. As the face of the satellite becomes fully illuminated to the observer, the integrated brightness exhibits a nonlinear surge in brightness that is believed to result from the disappearance of mutual shadowing among surface particles. The magnitude of this surge, known as the "opposition effect", is greater for a more porous surface.

One measure of how much radiation a satellite reflects is the geometric albedo, p, which is the disk-integrated brightness at "full moon" (or a phase angle of zero degrees) compared to a perfectly reflecting, diffuse disk of the same size. The phase integral, q, defines the angular distribution of radiation over the sky:

$$q = 2 \int_0^{\pi} \Phi(\alpha) \sin \alpha \, d\alpha$$

where $\Phi(\alpha)$ is the disk integrated brightness and α is the phase angle.

The Bond albedo, which is given by A = p x q, is the ratio of the integrated flux reflected by te satellite to the integrated flux received. The geometric albedo and phase integral are wavelength-dependent, while a true (or bolometric) Bond albedo is integrated over all. wavelengths.

Another groundbased photometric measurement, which has yielded important information on the satellites! surfaces, is the integrated brightness of a satellite as a function of orbital angle. For a satellite in synchronous rotation with its primary, the subobserver geographical longitude of the satellite is equal to the longitude of the satellite in its orbit. Observations showing significant albedo and color variegations for Io, Europa, Rhea, Dione, and especially Iapetus suggest that diverse geologic terrains coexist on these satellites. This view was confirmed by images obtained by the Voyager spacecraft.

Another important photometric technique is the measurement of radiation as one celestial body occults, or blocks, another body. Time resolved observations of occultations yield the flux emitted from successive regions of the eclipsed body. This technique has been used to map albedo variations on Pluto and its satellite Charon, and to map the distribution of infrared emission - and thus volcanic activity - on Io.

3. Radiometry

Satellite radiometry is the measurement of radiation which is absorbed and re-emitted at thermal wavelengths, The distance of each satellite from the sun determines the mean temperature for the equilibrium condition that the absorbed radiation is equal to the emitted radiation:

$$\pi R^2(F/r^2)(1-A) = 4\pi R^2 \varepsilon\sigma T^4$$

$$T = \left(\frac{(1-A)F}{4\sigma\varepsilon r^2}\right)^{1/4}$$

where R is the radius of the satellite, r is the sun-satellite distance, ϵ is the emissivity, σ is Stefan-Boltzmann's constant, A is the Bond albedo, and F is the incident solar flux (a slowly rotating body would radiate over 277 R^2). Typical mean temperatures in degrees Kelvin for the satellites are: the Earth's Moon, 280; Europa, 103; Iapetus, 89; the Uranian satellites, 60; and the Neptunian satellites, 45. For thermal equilibrium, measurements as a function of wavelength yield a blackbody curve characteristic of T: in general, the temperatures of the satellites closely follow the blackbody emission values. Some discrepancies are caused by a weak greenhouse effect (in the case of Titan), or the existence of volcanic activity (in the case of Io).

Another possible use of radiometric techniques, when combined with photometric measurements of the reflected portion of the radiation, is the estimate of the diameter of a satellite. A more accurate method of measuring the diameter of a satellite from Earth involves measuring the light from a star as it is occulted by the satellite. The time the starlight is dimmed is proportional to the satellite's diameter.

A third radiometric technique is the measurement of the thermal response of a satellite's surface as it is being eclipsed by its primary. The rapid loss of heat from a satellite's surface indicates a thermal conductivity consistent with a porous surface. Eclipse radiometry of Phobos, Callisto, and Ganymede suggests these objects all lose heat rapidly,

4. Polarimetry

Polarimetry is the measurement of the degree of polarization of radiation reflected from a satellite's surface. The polarization characteristics depend on the shape, size, and optical properties of the surface particles. Generally, the radiation is linearly polarized and is said to be negatively polarized if it lies in the scattering plane, and positively polarized if it is perpendicular to the scattering plane. Polarization measurements as a function of solar phase angle for atmosphereless bodies are negative at low phase angles; comparisons with laboratory measurements indicate this is characteristic of complex, porous surfaces consisting of multi-sized particles. In 1970, groundbased polarimetry of Titan that showed it lacked a region of negative polarization led to the correct conclusion that it has a thick atmosphere.

5. Radar

Planetary radar is a set of techniques which involve the transmittance of radio waves to a remote surface and the analysis of the echoed signal. Among the outer planets' satellites, the Galilean satellites and Titan have been observed with radar (see PLANETARY RADAR ASTRONOMY)

B. Spacecraft Exploration

1. Imaging Observations

Interplanetary mission to the planets and their moons have enabled scientists to increase their understanding of the solar system more in the past 20 years than in the previous total years of scientific history. Analysis of data returned from spacecraft has led to the development of whole new fields of scientific endeavor, such as planetary geology. From the earliest successes of planetary imaging, which included the flight of a Soviet Luna spacecraft to the far side of the Earth's Moon to reveal a surface unlike that of the visible side, devoid of smooth lunar plains, and the crash landing of a United States Ranger spacecraft, which sent back pictures showing that the Earth's Moon was cratered down to meter scales, it was evident that interplanetary imaging experiments had immense capabilities. Table 11 summarizes the successful spacecraft missions to the outer planetary satellites.

The return of images from space is very similar to the transmission of television images. A camera records the level of intensity of radiation incident on its detector's surface. A series of scans is made across the detector to create a two--dimensional array of intensities. A computer onboard the spacecraft records these numbers and sends them by means of a radio transmitter to the Earth, where another computer reconstructs the image.

The Pioneer spacecraft, which were launched in 1972 and 1973 toward an encounter with Jupiter and Saturn, returned the first disk-resolved images of the Galilean satellites. By far the greatest scientific advancements were made by the Voyager spacecraft, which returned thousands of images of the satellite systems of all four outer planets, the best of which are shown in Section IV. Color information for the objects was obtained by means of six broadband filters attached to the camera. The return of large numbers of images with resolution down to a kilometer has enabled geologists to construct geologic maps, to make detailed crater counts, and to develop realistic scenarios for the structure and evolution of the satellites.

2. Other Experiments

Although images are the most spectacular data returned by spacecraft, a whole array of equally valuable experiments are included in each scientific mission. For example, a gamma ray spectrometer aboard the lunar orbiters was able to map the abundance of iron and titanium across the Moon's surface. The Voyager spacecraft included an infrared spectrometer capable of mapping temperatures; an ultraviolet spectrometer; a photopolarimeter, which simultaneously measured the color, intensity, and polarization of light; and a radio science experiment that was able to measure the pressure of Titan's atmosphere by observing how radio waves passing through it were attenuated.

3. Future missions

In 1990, the Galileo spacecraft was launced toward Jupiter with an encounter in 1996. The mission consists of a probe to explore the Jovian atmosphere and an orbiter, which will make several close flybys of the Gal ilean satellites. The orbiter will contain both visual and infrared imaging devices, an ultraviolet spectrometer, and a photopolarimeter. The visual camera will be capable of obtaining images with 20 m resolution. The only other currently approved mission to the outer planet satellites is the Cassini mission to Saturn, due to be launced in 1997. The Cassini spacecraft will contain a probe to study the atmosphere and surface of Titan, and an orbiter to perform an in depth study of Saturn, its rings, and satellites. Its instruments include a camera, an imaging spectrometer, infrared and ultraviolet spectrometers, and a suite of fields and particles experiments. (see PLANETARY EXPLORATION MISSIONS).

IV. INDIVIDUAL SATELLITES

A. The Galilean Satellites of Jupiter

1. Introduction and Historical Survey

When Galileo trained his telescope on Jupiter he was amazed to find four points of light which orbited the giant planet. These were the satellites Io, Europa, Ganymede, and Callisto, planet-sized worlds known collectively as the Galilean satellites. Analysis of telescopic observations over the next 350 years revealed certain basic features of their surfaces. There was spectroscopic evidence for water ice on the outer three objects. The unusually orange color of Io was hypothesized to be due to elemental sulfur. Orbital phase variations were significant, particularly in the cases of Io and Europa, which indicated the existence of markedly different terrains on their surfaces. Large opposition effects observed on Io and Callisto suggested their surfaces were porous. The density of the satellites decreases as a function of distance from Jupiter (Table I).

Theoretical calculations suggested the satellites had differentiated to form silicate cores and (in the case of the outer three) ice crusts. The mantles of the outer three satellites possibly contain liquid water. The Voyager missions to Jupiter in 1977 and 1979 (Table II) revealed the Galilean satellites to be four unique geological worlds. Current knowledge of these objects is summarized in Figure 2. (see IO).

1. Europa

When the Voyager spacecraft encountered the second Galilean satellite, Europa, they returned images of bright, icy plains crisscrossed by an extensive network of darker fractures (see Figure 3). The existence of only a handful of impact craters suggested that geological processes were at work on the satellite until a few hundred million years ago or less. Europa is very smooth: The only evidence for topographical relief is the scalloped ridges with a height of a few hundred meters (see bottom of Figure 3).

Part of Europa is covered by a darker mottled terrain. Dark features also include hundreds of brown spots of unknown origin, and larger areas, which appear to be the result of silicate laden water erupting onto the surface (bottom left of Figure 3). The reddish hue of Europa is believed to be due to contamination by sulfur from Io.

The cracks, which planetary geologists have called lines, are a few km wide and 10-15% lower in albedo than the ambient terrain. Several have a brighter stripe down their centers. The darker albedo of the cracks is due to compositional differences: these areas are contaminated with silicate minerals or ices darkened by irradiation. The mechanism for the formation of lines is probably some form of tidal interaction and subsequent heating, melting, and refreezing. Calculations show that Europa may still have a liquid mantle. Although some scientists have discussed the possibility of a primitive life form teeming in the mantle, there is no evidence that life does indeed exist there.

2. Ganymede

The icy moon Ganymede, which is the largest Galilean satellite, also shows evidence for geologic activity. A dark, heavily cratered terrain is transected by more recent, brighter grooved terrain (see Figure 4). Although they show much diversity, the grooves are typically 10 km wide and one-third to one-half km high. They were implaced during several episodes between 3.5 and 4 billion years ago. Their formation may have occurred after a melting and refreezing of the core, which caused a slight crustal expansion and subsequent faulting and flooding by subsurface water.

The grooved terrain of Ganymede is brighter because the ice is not as contaminated with rocky material that accumulates over the eons from impacting bodies. The satellite is also covered with relatively fresh bright craters, some of which have extensive ray systems. In the cratered terrain there appear outlines of old, degraded craters, which geologists called palimpsests. The polar caps of Ganymede are brighter than the equatorial regions; this is probably due to the migration of water molecules released by evaporation and impact toward the colder high latitudes.

3. Callisto

Callisto is the only Galilean satellite that does not show evidence for extensive resurfacing at any point in its history. It is covered with a relatively uniform, dark terrain saturated with craters (Figure 5). There is, however, an absence of craters larger than 150 km. In a process known as viscous relaxation, ice slumps and flows over periods of billions of years and is apparently not able to maintain the structure of a large crater as long material which is primarily rock. One type of feature unique to Callisto is the remnant structures of numerous impacts. The most promonent of these, the Valhalla basin, is a bright spot encircled by as many as 13 fairly regular rings (Figure 5). Callisto may be contaminated by C-type or D-type material which accreted onto its surface during cometary or asteroidal impacts, or from ambient dust, The leading hemisphere of Callisto appears to be fluffier than the trailing side, possibly due to more intense meteoritic bombardment.

4. The Small Satellites of Jupiter

Jupiter has eleven known small satellites, including three discovered by the Voyager mission. They are all probably irregular in shape (see Table I). Within the orbit of Io are at least three satellites: Amalthea, Adrastea and Metis. Amalthea is a dark, reddish heavily cratered object reflecting less than 5% of the radiation it receives; the red color is probably due to contamination by sulfur particles from Io. Little else is known about its composition except that the dark material may be carbonaceous.

Adrastea and Metis, both discovered by Voyager, are the closest known satellites to Jupiter and move in nearly identical orbits just outside the outer edge of the thin Jovian ring, for which they may be a source of particles. Between Amalthea and Io lies the orbit of Thebe, also discovered by Voyager. Little is known about the composition of these satellites, but they are most likely primarily rock-ice mixtures. The three inner satellites sweep out particles in the Jovian magnetosphere to form voids at their orbital positions.

Exterior to the Galilean satellites, there is a class of four satellites moving in highly inclined orbits (Lysithea, Elara, Himalia, and Leda). They are dark objects, reflecting only 2 or 3% of incident radiation and may be similar to C- and D-type asteroids.

Another family of objects is the outermost four satellites, which also have highly inclined orbits, except they move in the retrograde direction around Jupiter. They are Sinope, Pasiphae, Carme, and Ananke, and they may be captured asteroids.

B. The Saturnian System

1. The Medium Sized Icy Satellites: Rhea, Dione, Tethys Mimas, Enceladus and Iapetus

The six largest satellites of Saturn are smaller than the Galilean satellites but still sizable -- as such they represent a unique class of icy satellite. Earth-based telescopic measurements showed the spectral signature of ice for Tethys, Rhea, and Iapetus; Mimas and Enceladus are close to Saturn and difficult to observe because of scattered light from the planet. The satellites! low densities and high albedos (Table I) imply that their bulk composition is largely water ice, possibly combined with ammonia or other volatiles. They have smaller amounts of rocky silicates than the Galilean satellites. Resurfacing has occurred on several of the satellites. Most of what is presently known of the Saturnian system was obtained from the Voyager flybys in 1980 and 1981. The six medium-sized icy satellites are shown to relative size in Figure 6.

The innermost medium-sized satellite Mimas is covered with craters, including one (named Arthur), which is as large as a third of the satellite's diameter (upper left of Figure 5). The impacting body was probably nearly large enough to break Mimas apart; such disruptions may have occurred on other objects. There is a suggestion of surficial grooves that may be features caused by the impact. The craters on Mimas tend to be high-rimmed, bowl shaped pits; apparently surface gravity is not sufficient to have caused slumping.

The next satellite outward from Saturn is Enceladus, an object that was known from telescopic measurements to reflect nearly 100% of the visible radiation incident on it (for comparison, the Moon reflects only about 11%). The only likely composition consistent with this observation is almost pure water ice, or other highly reflective volatile. When Voyager 2 arrived at Enceladus, it transmitted pictures to Earth which showed an object that had been subjected, in the recent geologic past, to extensive resurfacing; grooved formations similar to those on Ganymede were evident (see Figure 7). The lack of impact craters on this terrain is consistent with an age less than a billion years. It is possible that some form of ice volcanism is presently active on Europa. The heating mechanism is believed to be tidal interactions, perhaps with Dione. About half of the surface observed by Voyager is extensively cratered and dates from nearly 4 billion years ago.

A final element to the enigma of Enceladus is the possibility that it is responsible for the formation of the E-ring of Saturn, a tenuous collection of icy particles that extends from inside the orbit of Enceladus to past the orbit of Dione. The position of maximum thickness of the ring coincides with the orbital position of Enceladus. If some form of volcanism is presently active on the surface, it could provide a source of particles for the ring. An alternative source mechanism is an impact and subsequent escape of particles form the surface.

Tethys is covered with impact craters, including Odysseus, the largest known impact structure in the solar system. The craters tend to be flatter than those on Mimas or the Moon, probably because of viscous relaxation and flow over the eons under Tethys' stronger gravitational field. Evidence for episodes of resurfacing episodes is seen in regions that have fewer craters and higher albedos. In addition, there is a huge trench formation, the Ithaca Chasma, which may be a degraded from of the grooves found on Enceladus.

Dione, which is about the same size as Tethys, exhibits a wide diversity of surface morphology. Most of the surface is heavily cratered (Figure 8), but gradations in crater density indicate that several periods of resurfacing occurred during the first billion years of its existence. The leading side of the satellite is about 25% brighter than the other, due possibly to more intensive micrometeoritic bombardment on this hemisphere. Wispy streaks (see Figures 6 and 8), which are about 50% brighter than the surrounding areas, are believed to be the result of internal activity and subsequent emplacement of erupting material. Dione modulates the radio emission from Saturn, but the mechanism for this phenomenon is unknown.

Rhea appears to be superficially very similar to Dione (see Figure 6). Bright wispy streaks cover one hemisphere. However, there is no evidence for any resurfacing events early in its history. There does seem to be a dichotomy between crater sizes -- some regions lack large craters while other regions have a preponderance of such impacts. The larger craters may be due to a population of larger debris more prevalent during an earlier episode of collisions.

When Cassini discovered Iapetus in 1672, he noticed that at one point in its orbit around Saturn it was very bright, but on the opposite side of the orbit it nearly disappeared. He correctly deduced that one hemisphere is composed of highly reflective material, while the other side is much darker. Voyager images show that the bright side, which reflects nearly 50% of the incident radiation, is fairly typical of a heavily cratered icy satellite. The other side, which is centered on the direction of motion, is coated with a material with a reflectivity of about 3 - 4% (see Figure 9).

Scientists still do not agree on whether the dark material originated from an exogenic source or was endogenically created, One scenario for the exogenic deposit of material entails dark particles being ejected from Phoebe and drifting inward to coat Iapetus. The major problem with this model is that the dark material on Iapetus is redder than Phoebe, although the material could have undergone chemical changes after its expulsion from Phoebe to make it redder. One observation lending credence to an internal origin is the concentration of material on crater floors, which implies an infilling mechanism. In one model, methan erupts from the interior and is subsequently darkened by ultraviolet radiation.

Other aspects of Iapetus are unusual. It is the only large Saturnian satellite in a highly inclined orbit. It is less dense than objects of similar albedo; this fact implies a higher fraction of ice or possibly methane or ammonia in its interior.

2. The Small Satellites

The Saturnian system has a number of unique small satellites (Figure 10). Telescopic observations showed that the surface of Hyperion, which lies between the orbits of Iapetus and Titan, is covered with ice. Because Hyperion has a visual geometric albedo of 0.30, this ice must be mixed with a significant amount of darker, rocky material. It is darker than the medium-sized inner Saturnian satellites, presumably because resurfacing events have never covered it with fresh ice. Although Hyperion is only slightly smaller than Mimas, it has a highly irregular shape (see Table I). This suggests, along with the satellites battered appearance, that it has been subjected to intense bombardment and fragmentation. There is also good evidence that Hyperion is in nonsynchronous rotation -- perhaps a collision within the last few million years knocked it out of a tidally locked orbit (see CHAOTIC MOTION IN THE SOLAR SYSTEM).

Saturn's outermost satellite Phoebe, a dark object (Table I) with a surface composition probably similar to that of C-type asteroids, moves in a highly inclined, retrograde orbit, suggesting it is a captured object. Voyager images show definite variegations consisting of dark and bright (presumably icy) patches on the surface. Although it is smaller than Hyperion, Phoebe has a nearly spherical shape.

Three types of small satellites have been found only in the Saturnian system: the sheparding satellites, the co-orbitals, and the Lagrangians. All these objects are irregularly shaped (Figure 10) and probably consist primarily of ice. The three shepherds, Atlas, Pandora, and Prometheus, are believed to play a key role in defining the edges of Saturn's A and F rings. The orbit of Saturn's innermost satellite Atlas lies several hundred kilometers from the outer edge of the A-ring. The other two shepherds, which orbit on either side of the F-ring, not only constrain the width of this narrow ring, but may cause its kinky appearance.

The co-orbital satellites Janus and Epimetheus, which were discovered in 1966 and 1978, exist in an unusual dynamical situation. They move in almost identical orbits at about 2.5 Saturn radii. Every four years the inner satellite (which orbits slightly faster than the outer one) overtakes its companion. Instead of colliding, the satellites exchange orbits. The four--year cycle then begins over again. Perhaps these two satellites were once part of a larger body that disintegrated after a major collision.

Three other small satellites of Saturn orbit in the Lagrangian points of larger satellites: one is associated with Dione and two with Tethys. The Lagrangian points are locations within an object's orbit in which a less massive body can move in an identical, stable orbit. They lie about 60 degrees in front of and in back of the larger body. Although no other known satellites in the solar system are Lagrangians, the Trojan asteroids orbit in two of the Lagrangian points of Jupiter. (see SOLAR SYSTEM DYNAMICS).

C. The Satellites of Uranus

1. The medium-sized satellies of Uranus: Miranda, Ariel, Umbriel, Titania, and Oberon

The rotational axis of Uranus is inclined 98 degrees to the plane of the solar system; Earth-based observers currently see the planet and its system of satellites nearly pole-on. The orbits of Ariel, Umbriel, Titania, and Oberon are regular whereas Miranda's orbit is slightly inclined. Figure 11 is a telescopic image of the satellites typical of the quality attainable before the advent of spacecraft missions.

Theoretical models suggest that the satellites are composed of water ice, possibly in the form of methane clathrates or ammonia hydrates, and silicate rock. Water ice has been detected spectroscopically on all five satellites. Their relatively dark visual albedos, ranging from 0.13 for Umbriel to 0.33 for Ariel (see Table I), and gray spectrum indicates their surfaces are contaminated by a dark component such as graphite or carbonaceous material, Another darkening mechanism that may be important is bombardment of the surface by ultraviolet radiation. The higher density of Umbriel implies its bulk composition includes a larger fraction of rocky material than the other four satellites. Melting and differentiation have occurred on Miranda and Ariel, and possibly some of the other satellites. Models indicate that tidal interactions may provide an important heat source in the case of Ariel.

Miranda, Ariel, Oberon, and Titania all exhibit large opposition surges, indicating that the regoliths of these bodies are composed of very porous material, perhaps resulting from eons of micrometeoritic “gardening”. Umbriel's lacks a significant surge, which suggests its surface properties are in some way unusual. Perhaps its regolith is very compacted, or it is covered by a fine dust scatters optical radiation in the forward direction.

The Voyager 2 spacecraft encountered Uranus in January 1986 to provide observations of satellites that have undergone melting and resurfacing (see Figure 12). Two features on Miranda, known as “coronae”, consist of a series of ridges and valleys ranging in height from 0.5 to 5 km in height (Figure 13). The origin of these features is uncertain: some geologists favor a compressional folding interpretation, whereas others invoke a volcanic origin. Both Ariel, which is the geologically youngest of the five satellites, and Titania are covered with cratered terrain transected by grabens, which are fault-bounded valleys. Umbriel is heavily cratered and is the darkest of the satellites, both facts which suggest its surface is very old, although the moderate resolution images obtained by Voyager cannot rule out melting or other geologic activity. Some scientists have in fact interpreted small albedo variegations on its surface as evidence for melting events early in its history. Oberon is similarly covered with craters, some of which have very dark deposits on their floors. On its surface are situated faults or rifts suggesting resurfacing events (Voyager provided ambiguous, medium resolution views of the satellite). In general, the Uranian satellites appear to have exhibited more geological activity than the Saturnian satellites and Callisto, possibly because of the presence of methane, ammonia, nitrogen, or additional volatiles.

There is some evidence that Umbriel and Oberon, as well as certain regions of the other satellites, contain so-called D-type material, the organic-rich primordial constituent which seems to be ubiquitous in the outer solar system. D-type material is seen in the dark, red D-type asteroids, on the dark side of Iapetus, on Hyperion, and on specific areas of the larger satellites.

2. The small satellites of Uranus

Voyager 2 discovered 10 new small satellites of Uranus, including two which act as shepherding satellites for the outer (epsilon) ring of Uranus (Table I). All these satellies lie inside the orbit of Miranda. Images of two satellites, Puck and Cordelia, provided sufficient resolution to directly determine their radii (Table I). The sizes of the other bodies were derived by making the assumption that their surface brightnesses are equal to the other inner satellites and estimating the projected area required to yield their observed integral brightnesses. Puck appears to be only slightly non-spherical in shape. It is likely that the other small satellites are irregularly shaped. The satellites' visual geometric al bedos range from 0.04 to 0.09, which is sightly higher than that of Uranus's dark ring system. No reliable color information was obtained by Voyager 2 for any of the small satellites, although their low albedo suggests they are C-type objects.

D. The Satellites of Neptune

1. Introduction

Neptune has eight known satellites: one is the large moon Triton and the remaining seven are small, irregularly shaped bodies (Table I). The small satellites can be divided into two categories: the six inner bodies which move in highly regular, circular orbits close to Neptune (< 5 planetary radii), and the outer satellite Nereid, which moves in an eccentric orbit bringing it from 57 to 385 planetary radii from Neptune. Nereid's orbit is by far the most eccentric of any known natural satellite. Triton has an appreciable atmosphere, seasons, and currently active geologic processing. (see TRITON)

Only Triton and the outer satellite Nereid were known before the reconnaissance of Neptune by the Voyager 2 spacecraft in 1989. Nereid was discovered in 1949 by Gerard P. Kuiper at McDonald Observatory in Texas. In keeping with the theme of water and oceans for the Neptunian system, the satellite was named after the sea nymphs known in Greek mythology as Nereids. Larissa was probably detected in 1981 when it blocked a star astronomers were measuring for possible occultations by planetary rings. Because it was not subsequently observed or tracked, it was not classified as a satellite until its existence was confirmed by Voyager observations. Reliable ground based observations of Nereid were limited to estimates of its visual magnitude. Telescopic observations reported near the time of the Voyager encounter suggesting that one side of Nereid was significantly brighter than the other were not confirmed by Voyager images.

2. Orbital and bulk properties

The six inner satellites were all discovered within a few days during the Voyager encounter with Neptune in August 1989. They were given names of mythical nautical figures by the International Astronomical Union. For four of these satellites (Proteus, Larissa, Galatea, and Despina) as well as Nereid, Voyager images provided sufficient resolution to determine their dimensions (Table I). All five bodies are irregularly shaped. The sizes of Thalassa and Naiad were derived by making the assumption that their albedos are equal to the other inner satellites. The size of the satellites increases with the distance from Neptune. Proteus is the largest known irregular satellite in the solar system. The satellite has probably not been subjected to viscous relaxation; rather its mechanical properties have been determined by the physics of water ice, with an internal temperature below 110 K.

Spacecraft tracking of the six inner satellites, and groundbased observations of Nereid, provided accurate orbit determinations, which are listed in Table I. All the small inner satellites except Proteus orbit inside the so-called synchronous distance, which is the distance from Neptune at which the rotational spin period equals the Keplerian orbital. period. Proteus has, however, been tidally despun so that its rotational period equals its orbital period. Voyager observations show that Nereid is in non-synchronous rotation, although its rotational period has not yet been determined.

The masses of the satellites were not measured directly by Voyager. Limits may be obtained by assuming reasonable values for their bulk densities. These values range from 0.7 g/cc, corresponding to water ice with a bulk porosity of about 30%, to 2 g/cc, corresponding to water ice with a significant fraction of rocky material. If the satellites were formed from captured material, it is believed the higher density is more reasonable. In any case, the small satellites have less than 1% of the mass of Triton. The ring system of Neptune contains only a very small amount of mass, possibly one-millionth of the small satellites combined masses.

3. Appearance and composition

Figure 14 depicts the best Voyager images obtained for Proteus, with a resolution of 1.3 km per pixel. The large feature - possibly an impact basin - has a diameter of about 250 km. Close scrutiny of this image reveals a concentric structure within the impact basin. Possible ridge-like features appear to divide the surface. The regions of Proteus outside of the impact basin show signs of being heavily cratered.

The best image of Larissa was obtained at a resolution of 4.2 km/pixel and that of Nereid at a resolution of 43 km/pixel. Neither image has sufficient resolution to depict surface features. In 1988, 1989, and 1991, several groundbased observers reported large lightcurve amplitudes (up to factors of four), which they interpreted as significant albedo variegations on Nereid. Although there is some uncertainty (a factor of two at most) in comparing Voyager to ground based observations because the orientation of Nereid's spin axis is unknown, a lightcurve produced for Nereid from Voyager images over a 12 day period shows an amplitude of less than 15%.

Analysis of calibrated, integral Voyager measurements of the four inner satellites reveals that their geometric albedos are about 0.06, in the Voyager clear filter with an effective wavelength of about 480 nm. The integral brightness of Nereid is almost three times that of Proteus, which is slightly smaller; its geometric albedo is therefore -0.20.

The limited spectral data obtained by Voyager suggests that Proteus, Nereid, and Larissa are gray objects. The dark albedos and spectrally neutral character of the inner satellites suggests that they are carbonaceous objects, similar to the primitive C-type asteroids, possibly the Uranian satellite Puck, the satellites of Mars, and several other small satellites (Check these latter ones). Nereid, however, with its markedly higher albedo, probably has a surface of water frost contaminated by a dark spectrally neutral material. It is more similar to the differentiated satellites of Uranus than to the dark C-type objects. It is also similar in albedo, size, and color to Phoebe, the outer planet of Saturn which moves in an inclined, retrograde orbit, suggesting it is a captured object.

4. Origins and evolution

The irregular orbit of Nereid indicates it is probably a captured object. Jupiter, Saturn, and Neptune thus all appear to have outer, captured satellites.

The evolution of the inner satellites was likely punctuated by the capture of Triton. Initially, the inclinations and eccentricities of the satellites would have been increased by the capture, and subsequent collisions would have occurred. The resulting debris would then have reaccreted to form the present satellites. Models of the collisional history of the satellites suggest that with the exception of Proteus they are much younger than the age of the solar system. The heavily cratered surface which appears in the one resolvable Voyager image of these bodies (see Figure 14) does suggest they have undergone vigorous bombardment.

The only satellite which has been shown to have a dynamical relationship with the rings of Neptune is Galetea, which confines the ring arcs. The orbits of the satellites have probably evolved due to tidal evolution and resonances. For example, the inclination of Naiad is possibly due to its escape from an inclination resonance state with Despina.

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outer

TABLE 1. Summary of the Properties of the ~~Natural~~ Planetary Satellites

Satellite	Distance from primary (10^3 km)	Revolution period (days) R = Retrograde	Orbital eccentricity	Orbital inclination (degrees)	Radius (km)	Density (gm/cm³)	Visual geometric albedo	Discoverer	Year discov
Earth									
~~Moon~~	~~384.4~~	~~27.3~~	~~0.055~~	~~18 to 29~~	~~1738~~	~~3.34~~	~~0.11~~		
Mars									
~~M1 Phobos~~	~~9.38~~	~~0.32~~	~~0.018~~	~~1.0~~	~~14 × 10~~	~~1.9~~	~~0.05~~	~~Hall~~	~~1877~~
~~M2 Diemos~~	~~23.50~~	~~1.26~~	~~0.002~~	~~2.8~~	~~8 × 6~~	~~2.1~~	~~0.05~~	~~Hall~~	~~1877~~
Jupiter									
"J14 Adrastea	128	0.30	0.0	0.0	10		<0,1	Jewitt et a/.	1979
J16 Metis	128	0.30	0.0	0,0	20		<0,1	Synott	1979,
J5 Amalthea	181	0.49	0.003	0.4	131 × 86 × 73		0.05	Barnard	1892
J15 Thebe	221	0.68	0.0	0.0	30		<0.1	Synott	1979
J1 Io	422	1.77	0.004	0.0	1821	3.55	0.6	Galileo	I61O
J2 Europa	671	3.s5	0.000	0.5	1565	3.04	0.6	Galileo	1610
J3 Ganymede	1070	7.16	0.001	0.2	2634	1.93	0.4	Galileo	1610
14 Callisto	1880	16.69	0.010	0.2	2403	1.83	0.2	Galileo	1610
J13 Leda	11110	240	0.416	26.7	5			Kowal	1974
J6 Himalia	I 1470	251	0.158	27.6	85		0,03	Perrine	1904
J 10 Lysithea	11710	260	0.130	29.0	12			Nicholson	1938
J7 Elara	11740	260	0.207	24.8	40		0.03	Perrine	1904
J 12 Ananke	20700	617R	0.17	147	10			Nicholson	1951
J11 Carme	22330	692R	0.21	164	15			Nicholson	1938
J8 Pasiphae	23300	735R	0.38	145	18			Melotte	1908
J9 Sinope	23700	758R	0.28	153	14			Nicholson	1914
Saturn									
~~1981S13~~ S18 Pan	133	0.56						Showalter	1990
S15 Atlas	138	0.60	0.000	0.3	19X17X14		0.4	Voyager	1980
S16 Prometheus	139	0.61	0.002	0.0	74X50X34		0.6	Voyager	1980
S 17 Pandora	142	0.63	0.004	0.1	55X4X31		0.6	voyager	1980
S1O Janus	151	0.69	0.007	0.14	97 × 95 × 77	0.65	0.6	Dollfus	1966
S1 I Epimethus	151	0.69	0.009	0.34	69 × 55 × 55	0.65	0.3	Fountain and Larson	1978
S 1 Mimas	186	0.94	0.020	1.5	199	1.4	0.8	Herschel	1789
S 2 Enceladus	238	1.37	0.004	0.0	249	1.2	1.0	Herschel	1789
S 3 Tethys	293	1.89	0.(QO	1.1	S23	1.2	0.8	Cassini	1684
S14 Cal ypso	295	1.89	0.0	1?	15X8X8		0.6	Space Telescope Tm.	1980
S13 Telesto	295	1.89	0,0	1?	15x13x8		0.9	Smith et o/.	1980
S 4 Dione	377	2.74	0.002	0.0	360	1.4	0.55	Cassini	1684
S12 Helene	377	2.74	0.005	0.2	17x16x15		0.s	Laques and Lecacheux	1980
S5 Rhea	527	4.S2	0.001	0.4	764	1.3	0.65	Cassini	1672
S6 Titan	1220	15.94	0.029	0.3	2575	1.88	0.2	Huygens	1655
S 7 Hyperion	14s0	21.28	0.104	0.4	205 x 130X 110		0.3	Bond and Lassell	1848
S8 Iapetus	3560	79.33	0.028	14.7	718	1.2	0.4-0.08	Cassini	1671
S9 Phoebe	12950	550.4R	0.163	150	110		0.06	Pickering	1898
Uranus									
U6 Cordelia	49.7	0.33	0.0005	0.14	13			Voyager 2	1986
U7 Ophelia	53.2	0.37	0.001	0.09	15			voyager 2	1986
U8 Bianca	S9.2	0.43	0.0009	0.2	21			Voyager 2	1986
U 9 Cressida	61.8	0.46	0.0002	0.04	31		~0.04	Voyager 2	1986
U1O Desdemona	62.7	0.47	0.0002	0.2	27		~0.04	Voyager 2	1986
U] I Juliet	64.6	0.49	0.0006	0.06	42		~0.06	voyager 2	1986
U12 Portia	66.1	0.51	0.0002	0.09	54		~0.09	Voyager 2	1986
U13 Rosalind	69.9	0.36	0.00009	0.3	27		~0.04	Voyager 2	
(314 Belinda	73.3	0.62	0.0001	0.03	33			Voyager 2	1986
U15 Puck	86.0	0.76	0.00005	0.3	n		0.07	Voyager 2	1985
US Miranda	130	1.41	0.017	3.4	2%	1.2	0.35	Kuiper	1948
U1 Ariel	191	2.52	0.003	0.0	379	1.6	0.36	Lassell	1851
U 2 Umbriel	266	4,14	0.003	0.0	585	1.5	0.20	Lassell	1851
U3 Titania	436	8.71	0002	0,0	789	1.7	0.30	Herschel	1787
U 4 Oberon	583	13.46	0.001	0.0	761	1.6	0.22	Herschel	1787
Neptune									
N8 Naiad	48	0.30	0.003	4,74	27			Voyager 2	1989
N 7 Thalassa	50	0.31	0.0002	0.21	40			Voyager 2	1989
N5 Despina	52.5	0.33	0.0001	0.07	~~95~~ 74		0.05	Voyager 2	1989
N 6 Galatea	62	0.429	0.0001	0.0s	~~90~~ 79			Voyager 2	1989
N 4 Larissa	73.6	0.554	0.001	0.20	95 96		0.06	Voyager 2	1989
N3 proteus	117.6	1.12	0.0004	0.039	~~200~~ 208		0.0s	voyager 2	1989
N 1 Triton	354.8	5.875R	0.000015	157	1350	2.08	0.73	Lassell	1846
N 2 Nereid		360.1	0.753	6.7	I 70		0.14	Kuiper	1949
Pluto									
~~P1 Charon~~	~~19.1~~	~~6.4R~~	~~0?~~	~~92~~	~~606~~	~~1.8~~		~~Christy~~	~~1978~~

TABLE II. Summary of Major Flyby Missions to the Outer Planetary Satellites

Mission Name	Object	Encounter Dates
Pioneer 10	Jovian Satellites	1979
Pioneer 11	Jovian Satellites	1979
	Saturnian Satellites	1979
Voyager 1	Jovian Satellites	1979
	Saturnian Satellites	1980
Voyager 2	Jovian Satellites	1979
	Saturnian Satellites	1981
	Uranian Satellites	1986
	Neptunian Satellites	1989

FIGURE CAPTIONS

Figure 1: The relative sizes of the satellites of Jupiter, Saturn, Uranus, and Neptune.

Figure 2: A summary of current knowledge of the Galilean satellites.

Figure 3: A photomosaic of Europa assembled from Voyager 2 images.

Figure 4: A Voyager image of Ganymede, showing the dark cratered terrain and the brighter grooved terrain.

Figure 5: A Voyager 1 photomosaic of Callisto. The Valhalla impact basin, which is 600km wide, dominates the surface.

Figure 6: The six medium-sized icy Saturnian satellites. From the upper left, in order of size: Mimas, Enceladus, Tethys, Dione, Rhea and Iapetus.

Figure 7: A Voyager 2 photomosaic of Enceladus. Both heavily cratered terrain and recently resurfaced areas are visible.

Figure 8: The heavily cratered face of Dione is shown in this Voyager 1 image. Bright wispy streaks are visible on the limb of the satellite.

Figure 9: A Voyager 2 image of Iapetus, showing both bright and dark terrains.

Figure 10: The small satellites of Saturn. They are clockwise from far left; Atlas, Pandora, Janus, Calypso, Helene, Telesto, Epimetheus, and Prometheus.

Figure 11: Telescopic view of Uranus and its five satellites obtained by Ch. Veillet on the 154-cm Danish-ESO telescope. Outward from Uranus they are: Miranda, Ariel, Umbriel, Titania, and Oberon. Photograph courtesy of Ch. Veillet.

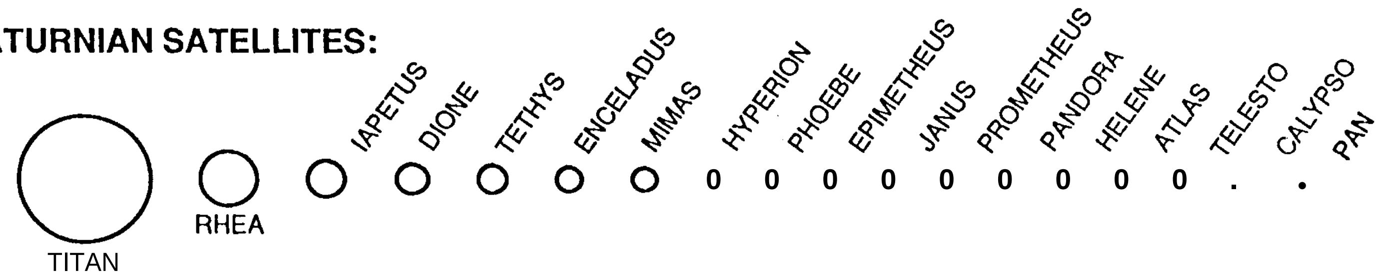
Figure 12: The five major satellites of Uranus, shown to relative size based on Voyager 2 images. They are, from left, Miranda, Ariel, Umbriel, Titania, Oberon.

Figure 13: A mosaic of Miranda produced from images taken by the Voyager 2 spacecraft at 30-40 thousand km from the moon. Resolution is 560 to 740 m. Older, cratered terrain is transected by ridges and valleys indicating more recent geologic activity.

Figure 14: The best Voyager image of Proteus, with resolution of 1.3 km per pixel.

JOVIAN SATELLITES::

SATURNIAN SATELLITES:



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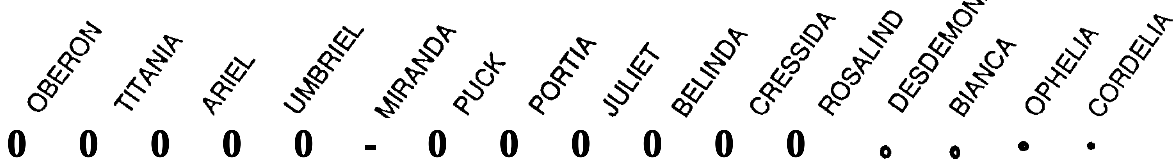
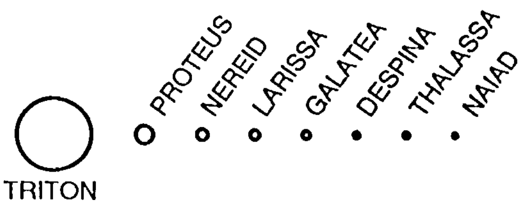
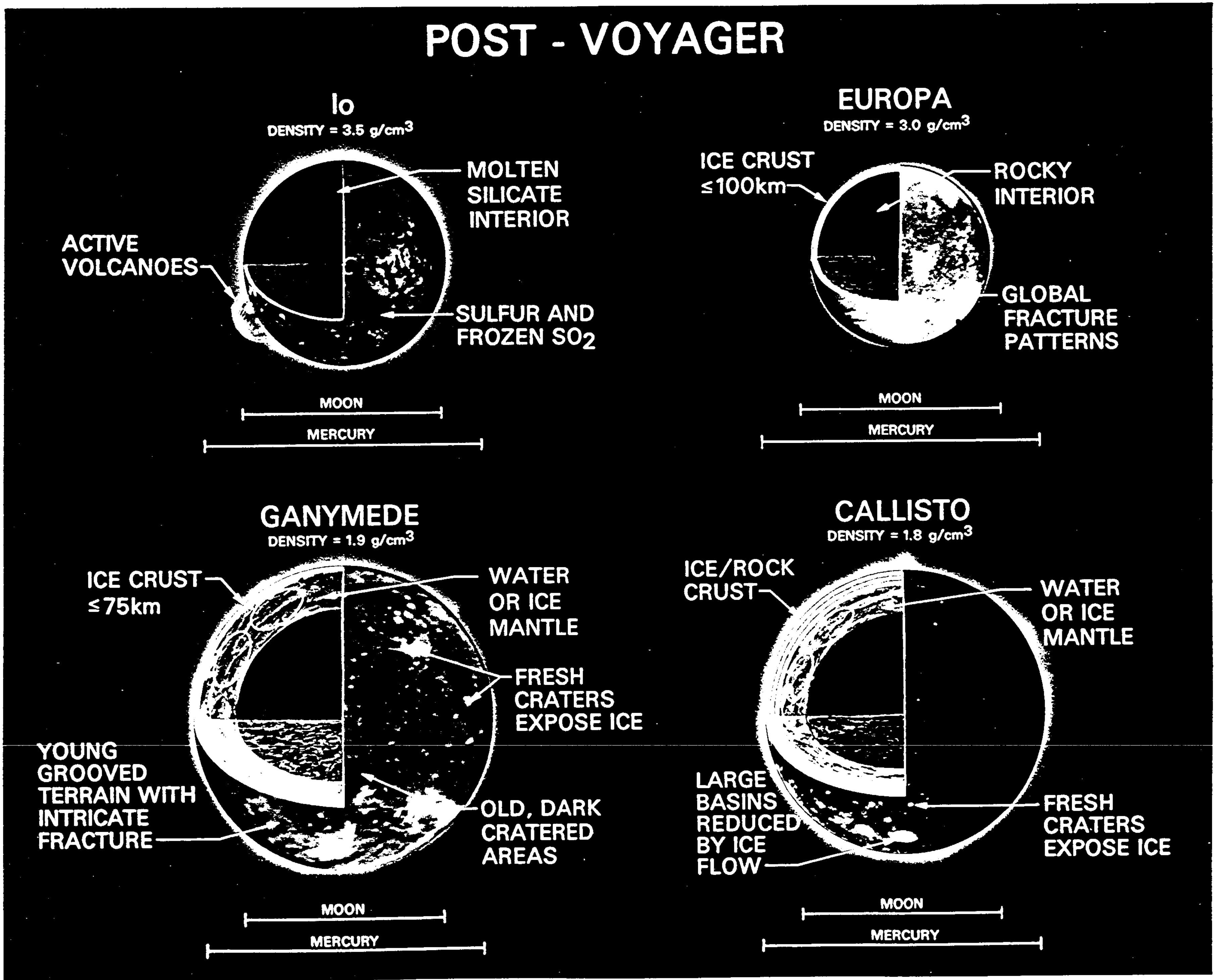
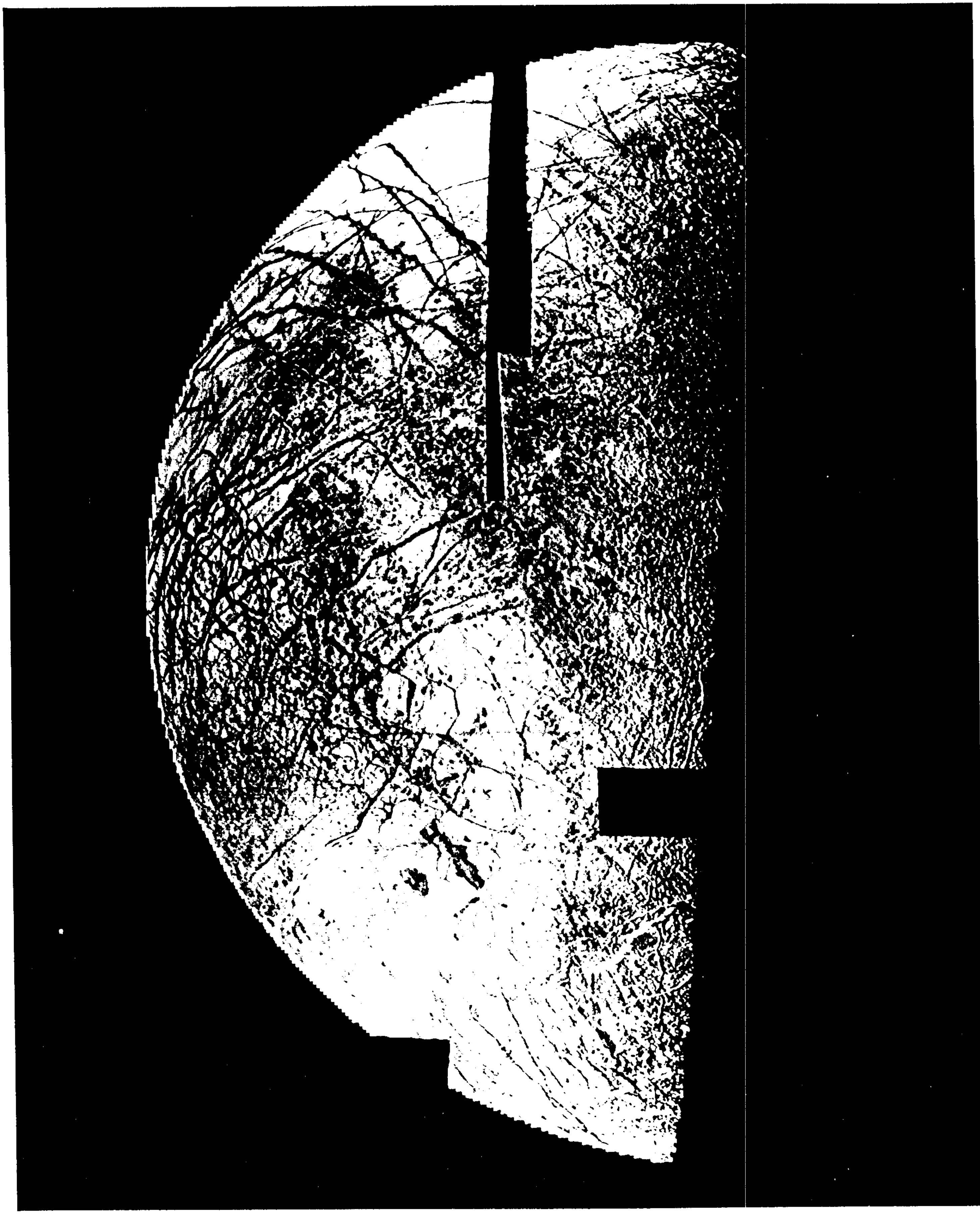
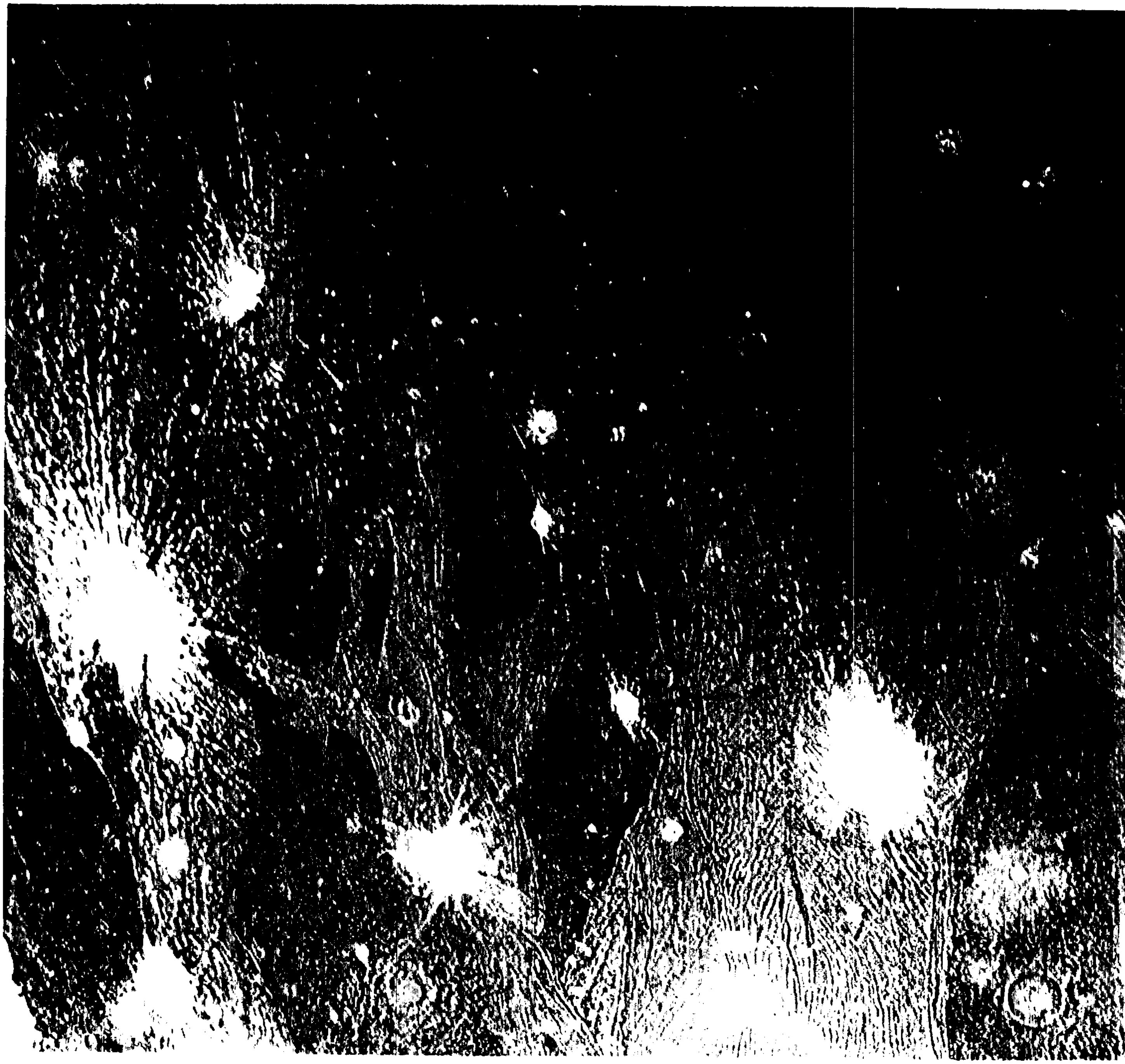


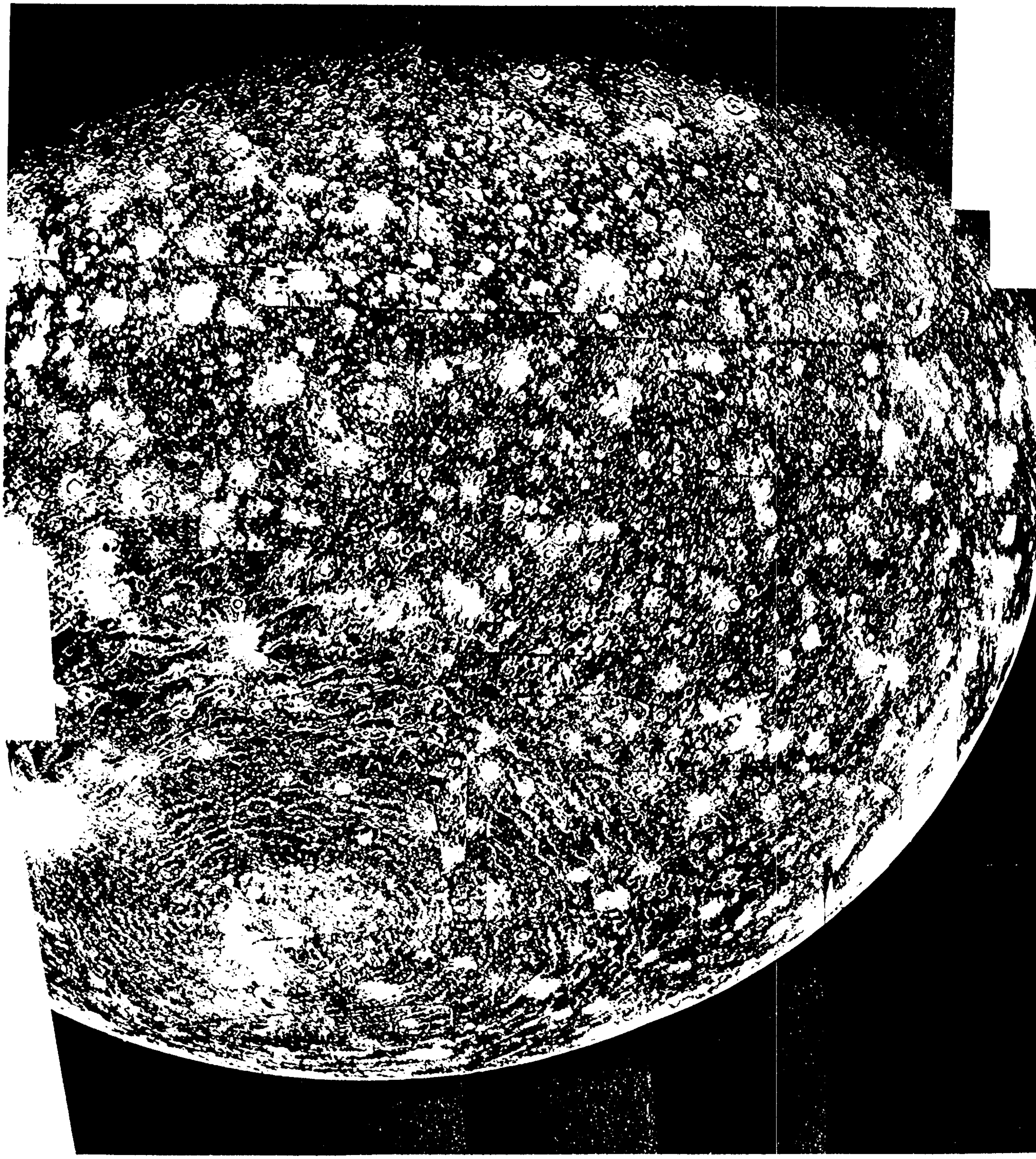
NEPTUNIAN SATELLITES:




POST - VOYAGER
Io
DENSITY = 3.5 g/cm3
MOLTEN SILICATE INTERIOR
ACTIVE VOLCANOES
SULFUR AND FROZEN SO2
MOON
MERCURY
EUROPA
DENSITY = 3.0 g/cm3
ICE CRUST ≤100km
ROCKY INTERIOR
GLOBAL FRACTURE PATTERNS
MOON
MERCURY
GANYMEDE
DENSITY = 1.9 g/cm3
ICE CRUST ≤75km
WATER OR ICE MANTLE
FRESH CRATERS EXPOSE ICE
YOUNG GROOVED TERRAIN WITH INTRICATE FRACTURE
OLD, DARK CRATERED AREAS
MOON
MERCURY
CALLISTO
DENSITY = 1.8 g/cm3
ICE/ROCK CRUST
WATER OR ICE MANTLE
LARGE BASINS REDUCED BY ICE FLOW
FRESH CRATERS EXPOSE ICE
MOON
MERCURY







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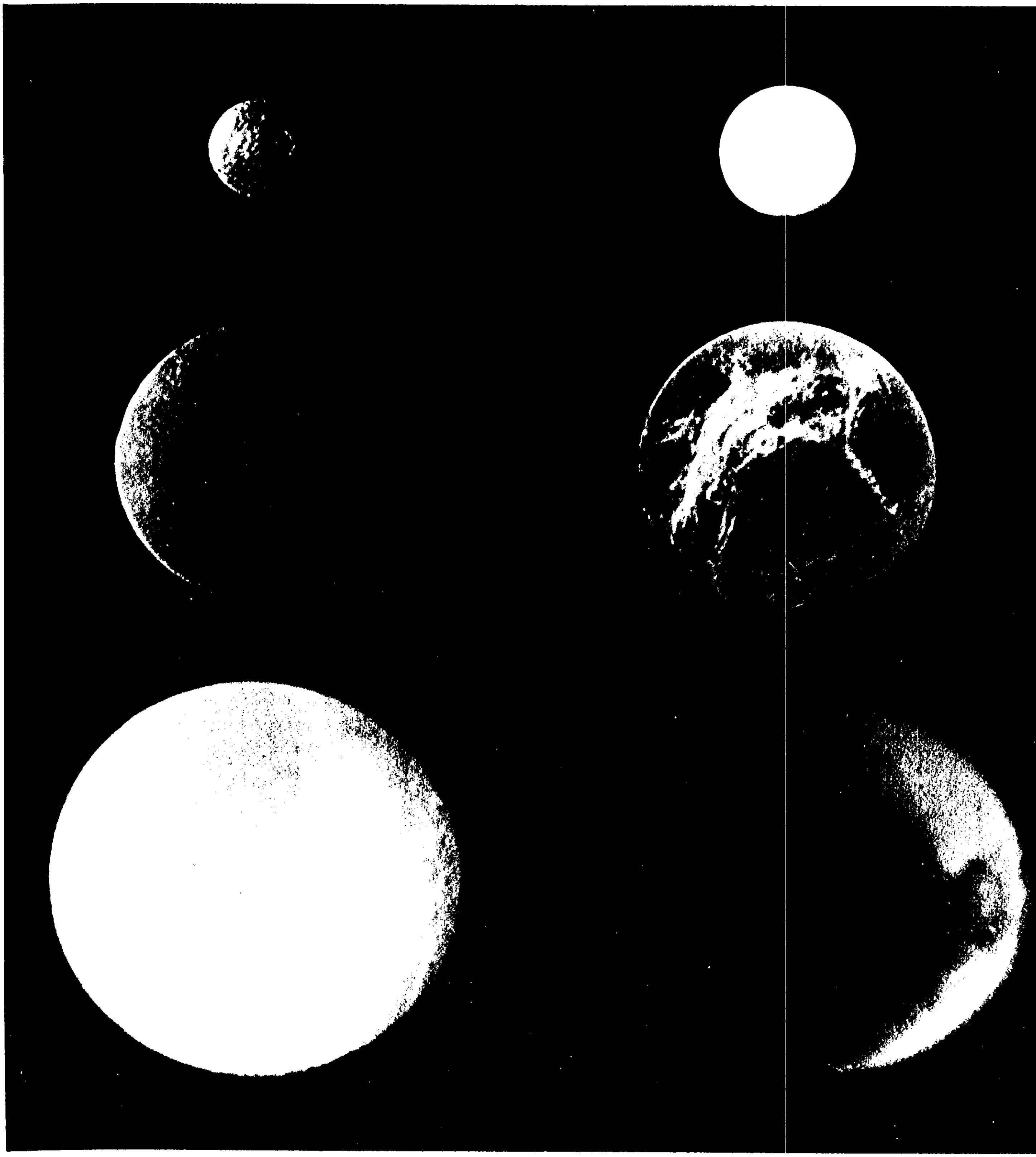

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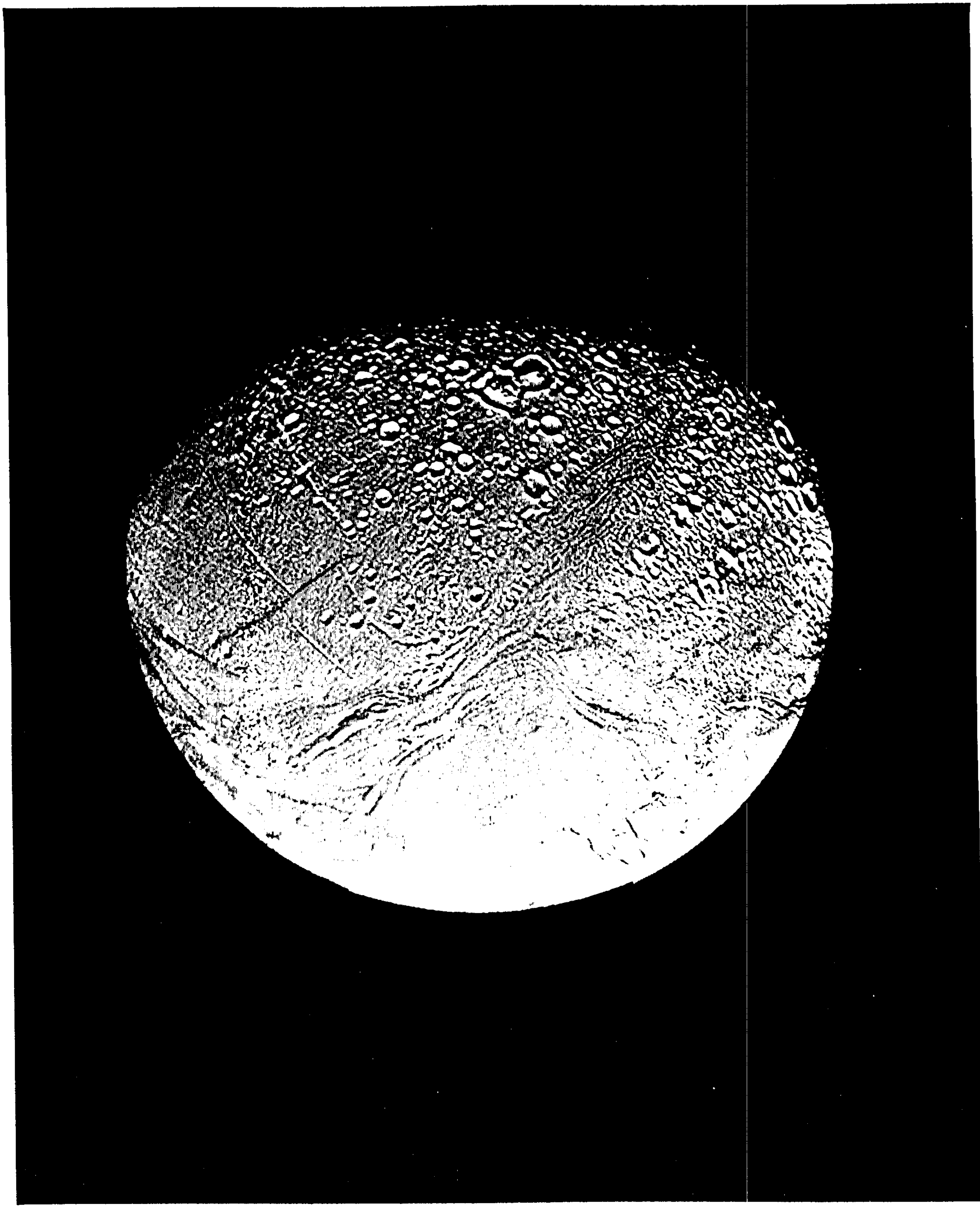

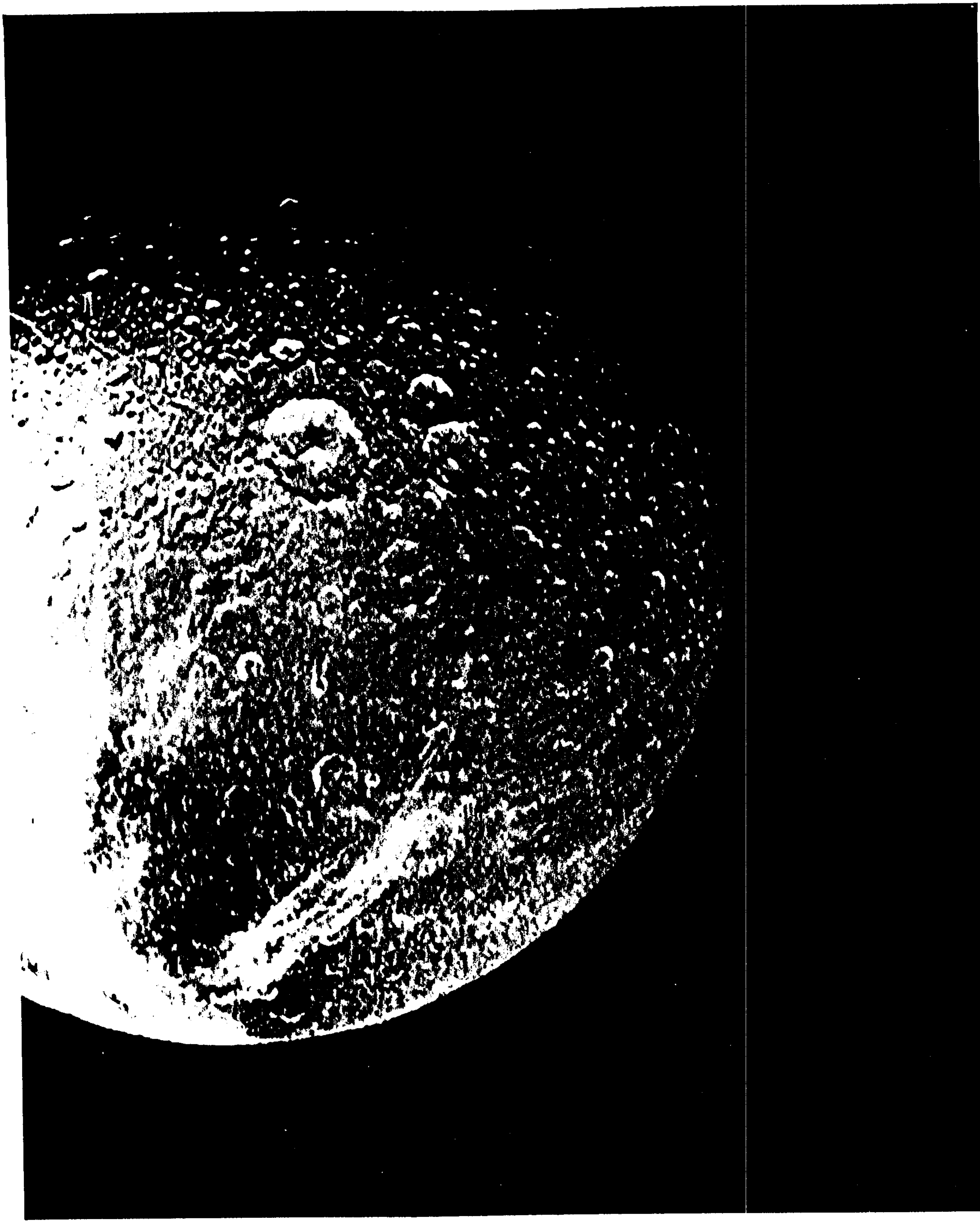

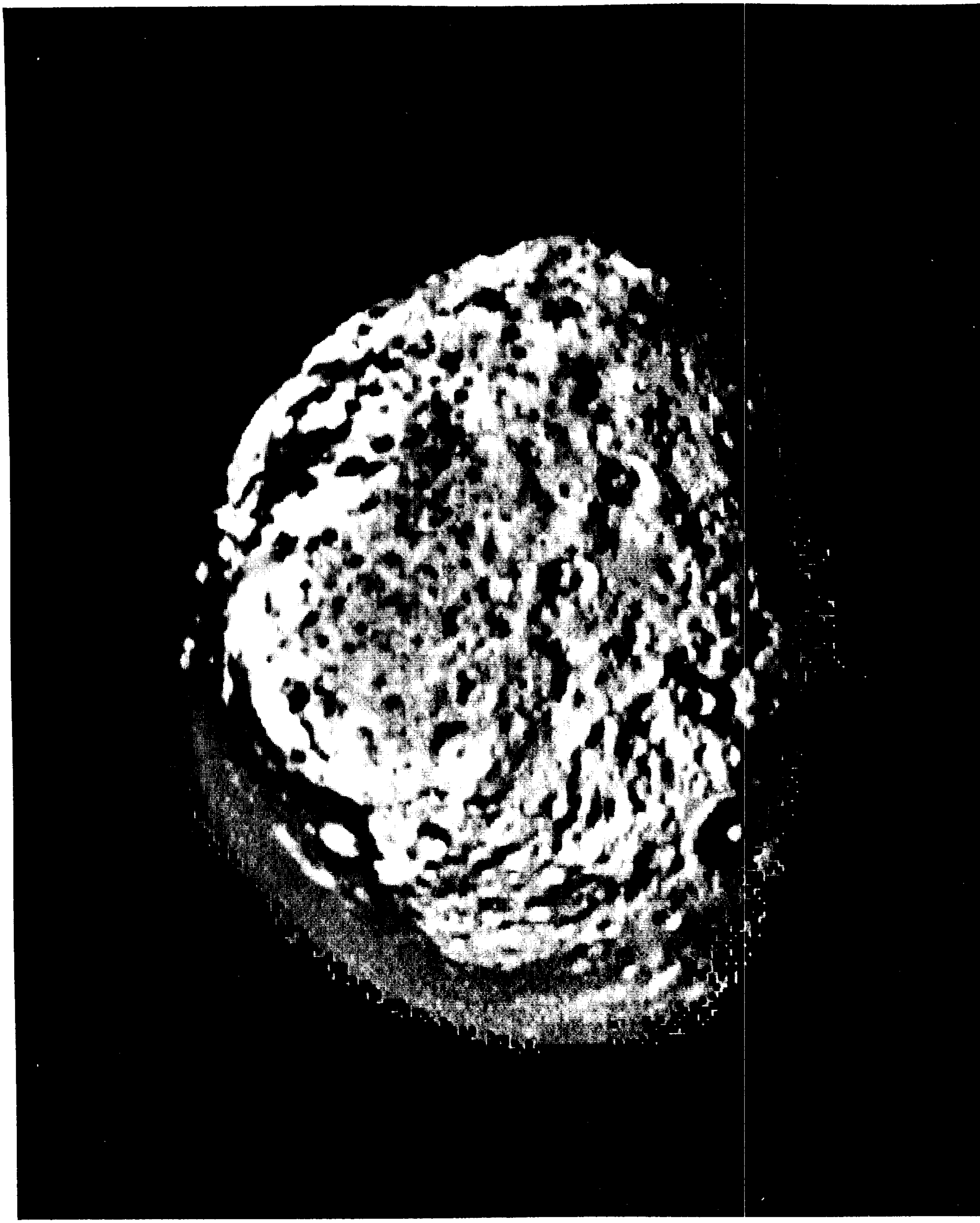

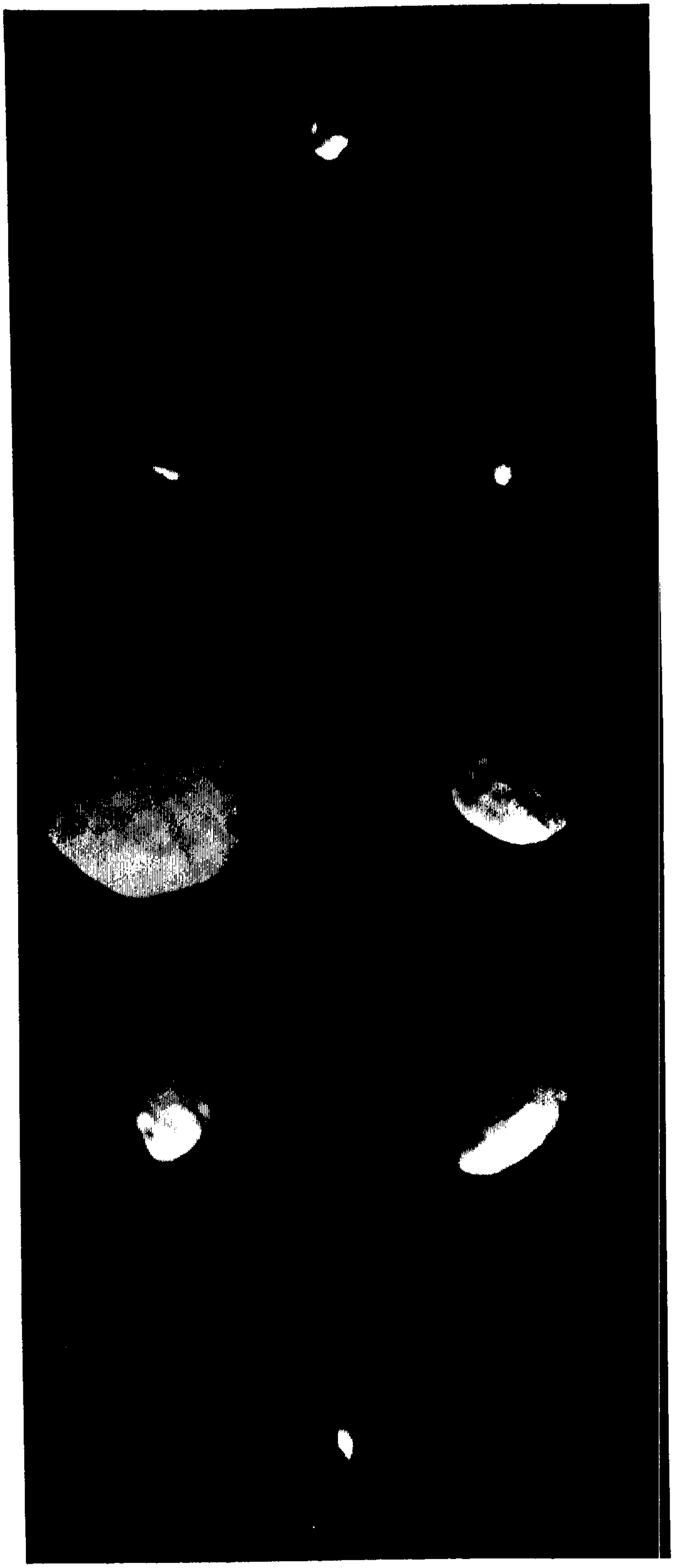

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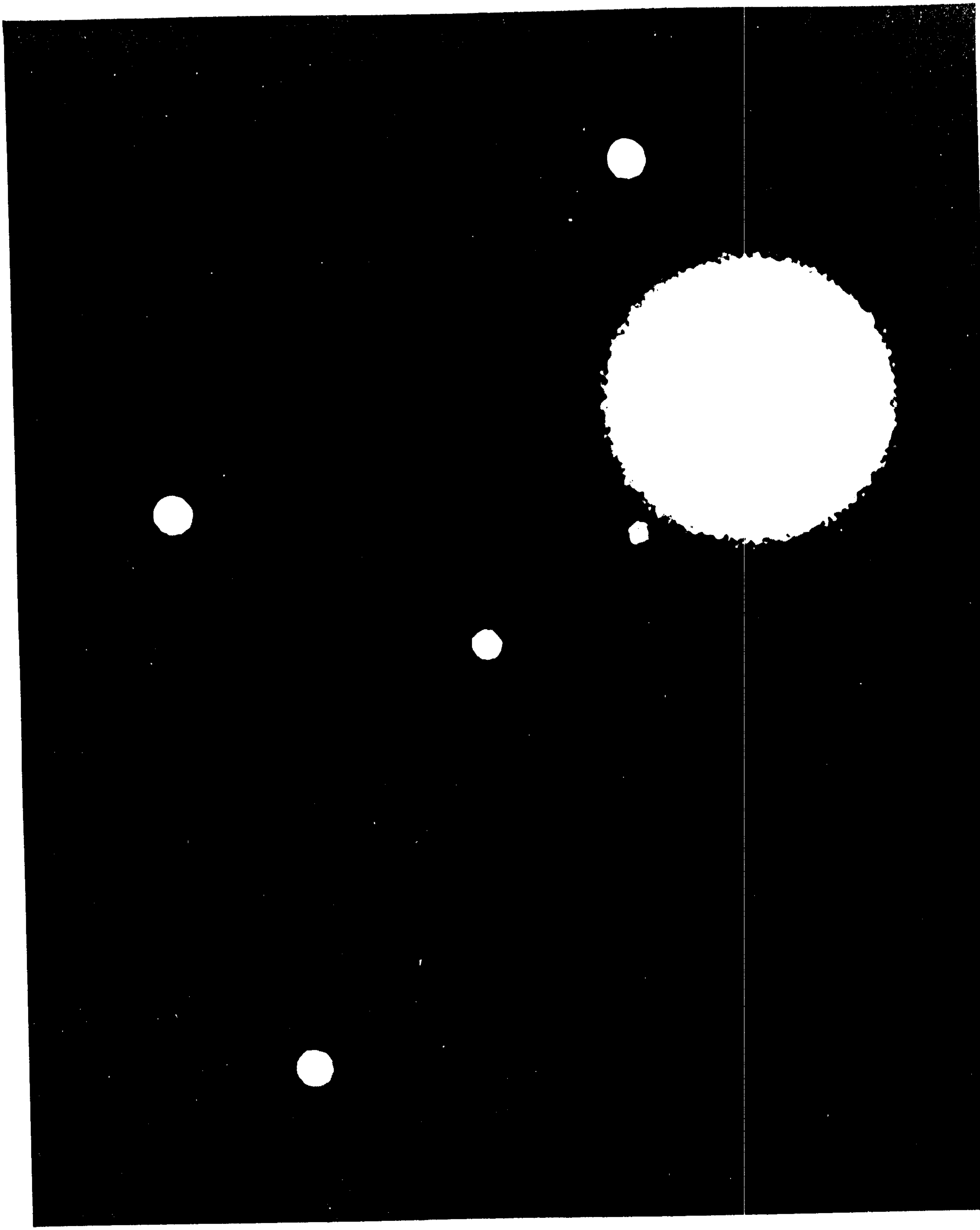

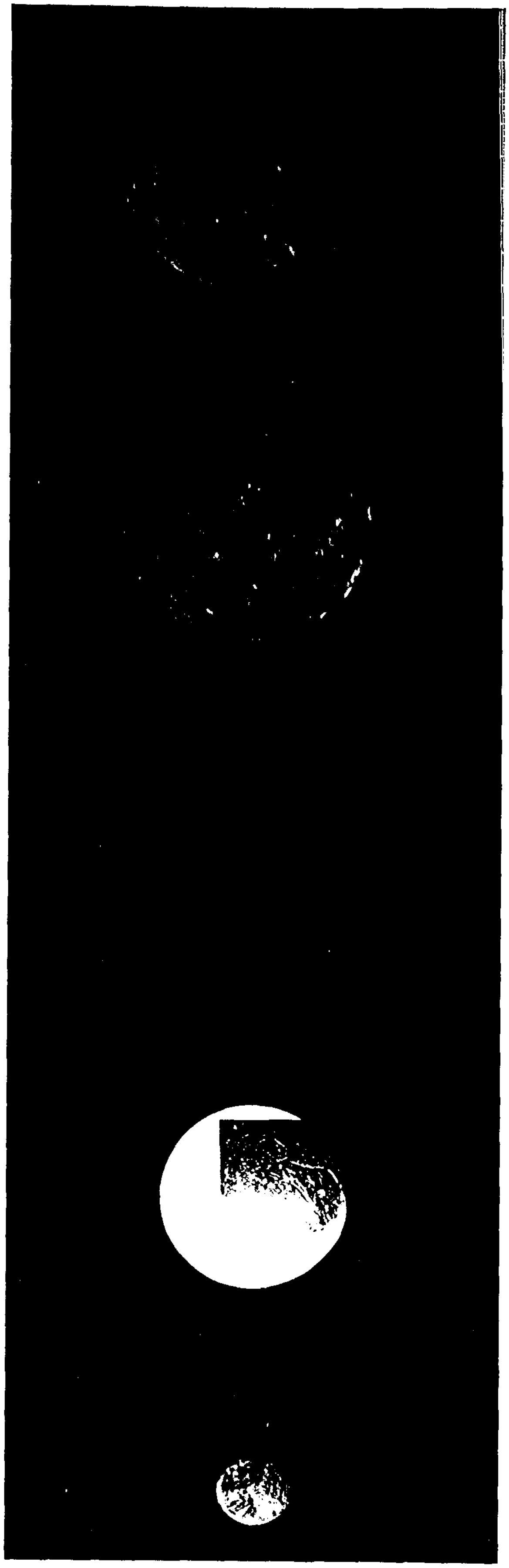

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